Knowledge Modeling Tool for Evidence-Based Design

Sanja Durmisevic, PhD, and Özer Ciftcioglu, PhD

Abstract

Aim of the Study: The aim of this study is to take evidence-based design (EBD) to the next level by activating available knowledge, integrating new knowledge, and combining them for more efficient use by the planning and design community. This article outlines a framework for a performance-based measurement tool that can provide the necessary decision support during the design or evaluation of a healthcare environment by estimating the overall design performance of multiple variables.
Background: New knowledge in EBD adds continuously to complexity (the “information explosion”), and it becomes impossible to consider all aspects (design features) at the same time, much less their impact on final building performance.
Research Questions: How can existing knowledge and the information explosion in healthcare—specifically the domain of EBD—be rendered manageable? Is it feasible to create a computational model that considers many design features and deals with them in an integrated way, rather than one at a time?
Approach: The found evidence is structured and readied for computation through a “fuzzification” process. The weights are calculated using an analytical hierarchy process. Actual knowledge modeling is accomplished through a fuzzy neural tree structure. The impact of all inputs on the outcome—in this case, patient recovery—is calculated using sensitivity analysis. Finally, the added value of the model is discussed using a hypothetical case study of a patient room.
Conclusion: The proposed model can deal with the complexities of various aspects and the relationships among variables in a coordinated way, allowing existing and new pieces of evidence to be integrated in a knowledge tree structure that facilitates understanding of the effects of various design interventions on overall design performance.
Key Words: *Evidence-based design, information explosion, knowledge modeling, fuzzy neural tree*

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Introduction

Designing a hospital using evidence-based design (EBD) should be an attainable goal. More and more such information is becoming available, and designers should be able to find essential answers. Yet there remain numerous open questions regarding the most effective design solutions. The growing body of evidence and the practicality of combining individual pieces of evidence do not make a designer’s task easier. Yet, the potential impact of the environment on the healing process is significant. Hospital boards of directors,

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together with planning and design teams, seek state-of-the-art knowledge to guide investment decisions.

It is plausible that financial gains could be achieved in the domain of healing environments if investments are properly directed. Hospitals need reliable evidence to support the current belief that proper investment during the initial phases of healthcare projects reduces life-cycle costs and improves service delivery and patient and staff experience and health. In the architectural, engineering, and construction (AEC) industry, business cases are being used to prove return on investment and the reduction of life-cycle costs. The AEC industry relies greatly on the expertise of different members of the project team. Some companies in this industry are trying to incorporate value-added services in their products, but they lack an integrated approach because of knowledge fragmentation, which is a trait of this industry. AEC is a slow-learning industry, gleaning little from its own mistakes because companies do not retain the knowledge held in different parts of the organization (Carrillo & Anumba, 2002). To apply project knowledge, there should be longer-term partnering between clients and suppliers, and technology that enables efficient knowledge management should be available (Surakka, 2006). The field of EBD is a good example of knowledge management that requires cross-disciplinary collaboration, where expert knowledge should become part of a larger and shared framework. At the same time, adequate technology should be used to enable information processing and the capture and reuse of knowledge.

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This article does not attempt to sum up all the evidence currently available; nor does it provide a final working model for the industry. Rather, it points the way toward dealing with available knowledge in a holistic way that is meaningful for the industry. This article puts forward a methodology to bring EBD to the next level. Using relevant existing evidence, which in this paper is structured as a knowledge model, it is possible to access and apply existing knowledge by developing a flexible and dynamic tool for decision makers' use when planning and designing new facilities or redeveloping existing ones.

Drawbacks of Current Evidence-Based Research and Practice

Healthcare institutions often rethink previous decisions to ensure that they are still appropriate. Decisions made years ago are not necessarily valid today because of the dynamics of changes in healthcare, technology, and lifestyles. For example, it is believed that today people spend much more time indoors than outdoors. People spend more than 80% of their time indoors (Myers &

Maynard, 2005). Additional estimates suggest that levels of several organics average two to five times higher indoors than outdoors; thus, poor indoor air quality, combined with the amount of time spent indoors, can have a negative impact on health (EPA, 2009). The majority of Sick Building Syndrome is related to poor indoor air quality. Some of the most common complaints of building occupants are headache, fatigue, difficulty concentrating, dry cough, eye irritation, nose or throat irritation, dry itchy skin, and dizziness (Baechler, 1991). Poor environmental features can slow the recovery process of patients and also result in higher rates of sick leave among staff. Both of these are essential issues to address in relation to healthcare buildings, which ideally should not be adding health stressors for patients/residents and staff.

During the last few decades there has been a growing interest in healing environments and EBD. Healing environments are not a new concept. Some 150 years ago, Florence Nightingale suggested that patients recovered more quickly when cared for in an environment that provided enough natural light, ventilation, and basic sanitation (Nightingale, 1860). Today a healing environment is considered an environment that contributes to the well-being of patients, staff, and visitors and that can be a factor in faster patient recovery (Altimier, 2004). In other words, healing environments could also be defined as environments that do not generate health stressors for staff and patients. This is relevant for healthcare institutions and hospitals in particular, but knowledge about the design parameters that help create such environments is scattered, heterogeneous, ambiguous, and contradictory, and it is therefore difficult to interpret. Ultimately, the question is: given a certain design composition, what would the expected impact be on, for example, patient recovery? In other words, how does a particular built environment perform, and does it advance or frustrate the recovery process? In the past, these questions initiated various types of studies that aimed to investigate the use of scientific evidence. As an ultimate goal, in combination these individual studies would lead to optimal building performance in terms of patient recovery or other health-related issues. This was the genesis of EBD, which is derived from evidence-based medicine (Malkin, 2003; Ulrich, Quan, Zimring, Joseph, & Choudhary, 2004). With this method, designers could use results from research to make decisions based on the best information available (Hamilton, 2003).

However, the domains of healing environments and EBD confront several challenges. First, numerous articles that present "evidence" on the effect of environmental features on health outcomes appear each year, but the great majority of these studies do not provide credible data, because they are not considered rigorous studies. Recently several attempts have been made to select the most credible evidence based on a thorough literature review and strict evaluation procedures (Dijkstra, Pieterse, & Pruyn, 2006; Rashid & Zimring, 2008; Ulrich et al., 2004; van den Berg, 2005). Almost every year, updated reviews that evaluate recent research are published. As new evidence appears, it becomes apparent that there is still no adequate methodology available that integrates all credible findings holistically to demonstrate the possible effects on health outcomes and the benefits and detriments of certain design decisions.

When new evidence appears, the problem is not additional knowledge; rather, the challenge is managing and combining new and existing knowledge to provide *meta-knowledge*. One of the main difficulties with EBD as it is currently practiced as a design methodology is that it is based on isolated studies that point to individual factors in specific cases. The studies say nothing about the importance of a particular design feature (later in the text referred to as *aspect*), in relation to other aspects or studies; furthermore, these isolated studies say nothing about the possible relationships between these aspects. The current approach does not provide a hint about dealing with multiple aspects at the same time and the possible cumulative effect of several aspects on the final outcome.

To conclude:

- There is no adequate methodology to deal with different environmental aspects in a holistic way.
- There is a lack of knowledge on the cumulative effect of various environmental aspects on health.
- There still is no adequate tool for the efficient knowledge management and knowledge modeling of EBD data based on individual studies.

Challenges for a Holistic Approach

Cause-and-effect relationships are often unclear because of the number of variables associated with the built environment, health outcomes, and the complex relationship among them. Therefore, the development of a theoretical framework that considers not only isolated elements of the built environment but also design compositions and social-organizational environments potentially offers a new direction. In other words, there is a need for a holistic or systems approach where the system as a whole determines how the parts behave and what the impact on the final outcome will be.

When approaching a problem from a holistic point of view, information explosion becomes a significant challenge, and this is where most studies end. The end point of this previous research is the starting point of this article. As McManus stated during his keynote speech at the HealthDesign08 conference: “We are undergoing a radical shift into the mature information age, and we are living in a time of information abundance and overload. In fact, by 2010, the codified information base of the world is expected to double every 11 hours” (McManus, 2008). “Evidence” has increased in recent decades, and if it continues at this rate, EBD as currently practiced will become obsolete because of the information explosion and its inherent complexity. Numerous new studies are being conducted, but this mushroom-like growth of information makes it impossible for designers and healthcare decision makers to keep track of state-of-the-art developments. The practical interpretation of results is often difficult in itself. Perhaps this is why more and more extensive literature reviews in the field are published: to attempt to keep up

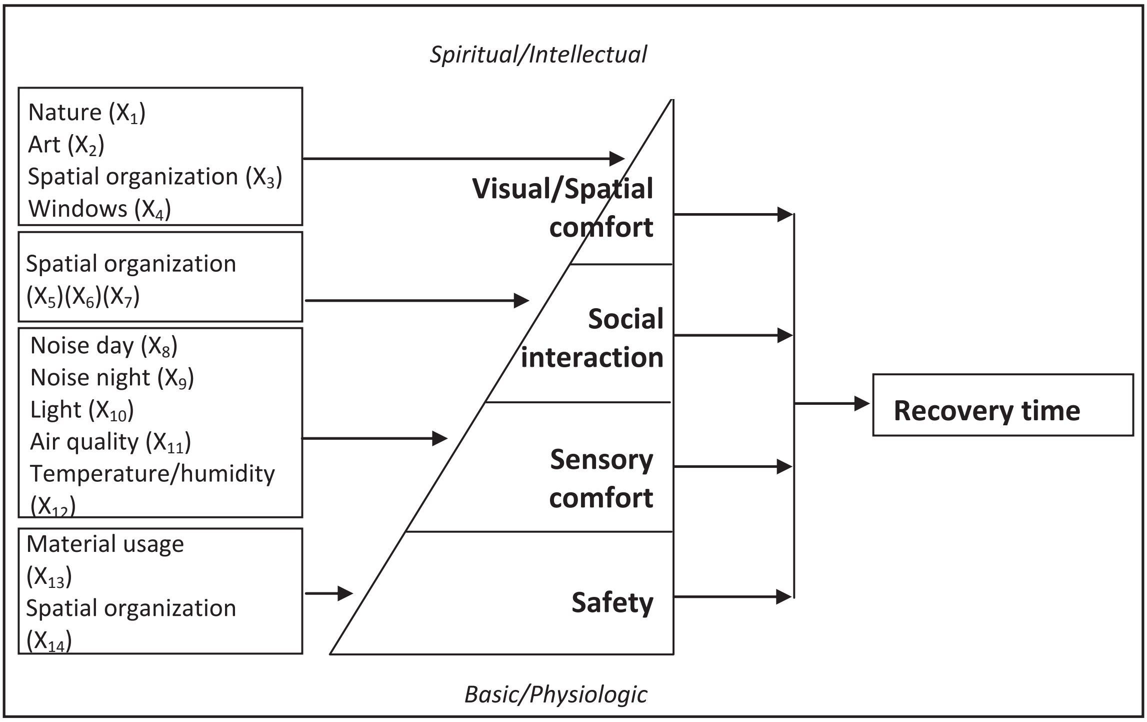

Figure 1. Environmental factors structured using Maslow's hierarchy of needs. The (X_n) values indicate inputs for the knowledge model (see Figure 2).

to date with the latest research. Should this continue forever, or should there be an attempt to tame the complexity inherent in the information explosion? Taming complexity is only possible through the application of *knowledge technology.* Unless there is movement in this direction, the field will be mired in a sea of information, unable to put words into action, because unstructured information tends to paralyze rather than facilitate needed progress. To be able to deal with these problems, there must be a focus on the development and integration of knowledge technology to support the AEC industry and decision makers as they plan and design healthcare facilities.

Fuzzy Neural Knowledge Model Structure

For demonstration purposes, this paper uses Maslow's hierarchy of needs (Maslow, 1943) as a way to structure and link environmental factors and the recovery time of patients. A patient may be treated medically, but the recovery and cure process also depends on the environment in which a patient is recovering (Hagerman et al., 2005; Ulrich, 1984; Williamson, 1992). Besides indoor air quality, which was mentioned earlier, health stressors can also be found in other domains. Figure 1 presents several environmental factors for which the literature supports a relationship with the recovery time of patients. These factors are structured using an adapted version of Maslow's hierarchy of needs (Maslow, 1943).

Table 1 provides short descriptions of the articles and evidence used to develop the knowledge model in this paper.

Knowledge modeling consists of two basic steps. In the first step, a structure is defined. In the second step, existing research results from a particular study are integrated into the knowledge model, bearing in mind its position in the model and possible relationships.

As an example, an adapted version of Maslow's hierarchy of needs was used as a starting point for model development. It is developed further, taking into consideration environmental features

Table 1. Articles Used for Knowledge Modeling

DIMENSION	ASPECT	EVIDENCE
Safety	Material usage	Use of some materials in construction may be related to infection outbreaks in hospitals, especially during reconstruction. In one study, the source of infection was presumed to be the disturbance of an accumulation of spores in fibrous insulation material above the perforated ceiling (Humphreys et al., 1991).
	Spatial organization	Single-bed rooms are preferred in terms of reducing/preventing infection. Decentralized nursing stations and single-bed rooms designated to support family presence may help to reduce falls (Ulrich et al., 2004).
Sensory Comfort	Noise	For continuous noise (in patient rooms) the World Health Organization (WHO) guideline is based on 35 dB during the day and 30 dB at night. In the night situation, noise peaks should not exceed 45 dB (Berglund, Lindvall, & Schwela, 1999). However, research from Berg (2001) showed that not only low decibel levels are important, but also reverberation time. Low dB levels (38–40 dB), when combined with longer reverberation times, significantly fragmented and worsened the sleep of volunteers in patient rooms (Berg, 2001; Ulrich et al., 2004).
	Temperature/ humidity	It is assumed that patients generally find a stable temperature of 21.5°C–22°C and a humidity rate of 30–70% comfortable (Rashid & Zimring, 2008)
	Light	Long-term (up to 3.5 years) daily supplementation of the circadian synchronizers light (± 1000 lux) and/or melatonin (2.5 mg) on cognition and actigraphic estimates of sleep-wake rhythms of 189 mostly demented elderly residents of group facilities in 12 nursing homes. Light ameliorated depressive symptoms by 19% and the limitations of activities of daily living by 11% (Riemersma-Van der Lek, 2007). Important for execution of the tasks (less medication error at 1500 lux than at lower lux levels) (Ulrich et al., 2004).
	Air quality	In all building types a ventilation rate of less than 10 liters/second per person proves to lead to health problems and adversely affects the perception of air quality (Rashid & Zimring, 2008).

Table 1. *(continued)*

Social Interaction	Spatial organization	Interaction with family members and family participation in care receive higher scores in single-patient rooms (52.1% very high and 43.8% high) compared to a multiple bedroom (only 2.7% very high and 12.3% high). Single rooms were also more flexible for accommodating family members (Chaudhury, Mahmood, & Valente, 2003). Suitability for patient examination and interaction with staff also receive high scores for private rooms (84.9% very high, 15.1% high) compared to a multiple bedroom (0% very high, 6.8% high) (Chaudhury et al., 2003). Another study of Barlas, Sama, Ward, and Lesser (2001) compared the visual and auditory privacy of patients at the emergency department who were assigned either to multi-bed spaces with curtain partitions or rooms with solid walls. About 5% of patients who were assigned to spaces with curtains reported that they have withheld some information regarding their medical history and refused parts of their physical examinations due to a lack of privacy (Barlas et al., 2001). This implies that lack of privacy can reduce patient safety (Ulrich et al., 2004). A limited number of (good) studies in psychiatry and nursing homes show that a suitable setting of movable chairs in dining rooms promotes social interaction and improves eating behavior (particularly sufficient food intake by the elderly). The often-chosen setting of chairs in rows along the walls in waiting rooms will also discourage social interaction rather than promote it. This suggests that additional spaces should be provided that enable social interaction with other patients and staff (CBZ, 2008).
Visual/Spatial Comfort	Nature	Patients recovering from abdominal surgery recovered faster, had better emotional well-being, and required fewer strong pain medications if they had bedside windows with a nature view (looking onto trees) than if their windows looked onto a brick wall (Ulrich, 1984).
	Art	Distraction therapy with nature sights and sounds significantly reduces pain in patients undergoing flexible bronchoscopy (Diette, Lechtzin, Haponik, Devrotes, & Rubin, 2003). Heart-surgery patients in ICU who were assigned to a room with a picture of a landscape scene with trees and water reported less anxiety/stress and needed fewer strong doses of pain medication than a control group assigned no pictures. The group of patients assigned an abstract picture had worse outcomes compared to the control group (Ulrich, 1991).
	Spatial organization	Single rooms are preferred over multiple rooms in terms of privacy and control over the environment (Barlas et al., 2001; Chaudhury et al., 2003).
	Windows	Sufficient informative views of the environment were preferred, thereby allowing one to "project" into the scene. By contrast, insufficiently windowed spaces were characterized by sills high above the floor and distant from the viewer, and views obstructed by nearby walls, screens, furnishings, and so on. Even when minimum standards are met in technical terms, the dysfunctionality of such windows appears to be the equivalent of having no window whatsoever (Verderber, 1986).

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that have an influence on patient recovery. Because this is only an example, no specific patient group was examined; rather, several research results that indicated the relationship between the built environment and faster recovery were considered, taking into account basic human need, indicating validity for a wide group of users. In general, for actual modeling, it is important to distinguish between information that is usually valid for any patient group that fits Maslow's description of basic human needs, and information that may be valid only for a specific patient group. The systematization and grading scheme are only starting points for knowledge modeling. A knowledge base is created through this process; that is, each particular aspect that is part of the model is recorded in a meaningful form that can be interpreted easily by the end user. This is where outstanding evidence is extracted, interpreted, and "fuzzified." To understand the fuzzification process, one must be familiar with fuzzy logic.

Fuzzy set theory and fuzzy inference systems were introduced by Zadeh (1965, 1973). Fuzzy logic explicitly aims to model the imprecise form of human reasoning and decision making. The fundamental concept of fuzzy logic is known as the *linguistic variable*, a variable that takes its values from spoken language. Such variables need to be transformed into numerical values for computation. A variable is called *numeric* if its values are numbers (e.g., 5 meters or 10 degrees). A variable is called *linguistic* if its values are expressed as linguistic terms, such as high, wide, or cold. Because computers can deal only with numbers, it is necessary to associate numbers with the linguistic variables. With membership functions, it is possible to associate grades with linguistic variables and thus transform them into numeric values. Membership functions take values between 0 and 1, meaning that the grading is done on a scale between 0 and 1.

These processes result in the representation of information. This representation is not yet ready to be used in a meaningful way, because at the level of systematization and grading there are no rules to apply to the information. In other words, the relationship between the factors is not yet modeled, which makes the information at hand difficult to interpret and to apply in a knowledge form. This is a major problem of EBD, because it lacks a holistic approach to indicate how important a particular design feature is in relation to all the others. A holistic approach requires a hierarchy formation, which becomes a basic rule of this particular knowledge model. Establishing a hierarchy can be done using the Analytical Hierarchy Process (AHP) (Saaty & Alexander, 1981; Saaty & Vargas, 1982). The AHP is a technique to compute a priority vector, ranking the relative importance of the factors being compared. In AHP computations, expert knowledge plays an essential role. The model weights are determined with AHP. Based on these weights, the structure of the knowledge model is established as a fuzzy neural tree structure (Figure 2).

A fuzzy neural tree is composed of nodes and weights that are connection links between a pair of nodes. There are two types of nodes, categorized as *terminal* and *nonterminal*. Each terminal node, also called a leaf, is labeled with an element from the terminal set $T = \{x_1, x_2, \ldots, xn\}$, where x_1 is the *i*-th component of the external input *x*, which is a vector. Each link (*i,j*) represents a directed connection from node *i* to node *j*. The value w_{ij} is associated with each link. In a neural tree, the root node is an output unit and the terminal nodes are input units. The nonterminal node outputs are computed in the same way as in a feed-forward neural network. In this way, neural trees can represent a broad class of feedforward networks that have irregular connectivity and nonstrictly layered structures. In particular, in the present work the nodes are similar to those used in a radial basis functions network with the Gaussian basis functions.

In the neural tree considered in this work, the output of *i*-th terminal node is denoted μ_i and it is introduced to a nonterminal node. A nonterminal node consists of a Gaussian radial basis function, which is in general form

$$f(X) = we^{-\frac{1}{2\sigma^2}(X-c)^2} \tag{1}$$

where *c* is the center of the basis function. The Gaussian basis function is of particular interest and used in this research because of its relevance to fuzzy logic. The width of the basis function σ is used to measure the uncertainty associated with the node inputs designated as external input *X*. The output of *i*-th terminal node μ_i is related to X_i by the relation

$$X_i = \mu_i w_{ij} \tag{2}$$

where w_{ij} is the weight connecting terminal node *i* to nonterminal node *j*. It connects the output

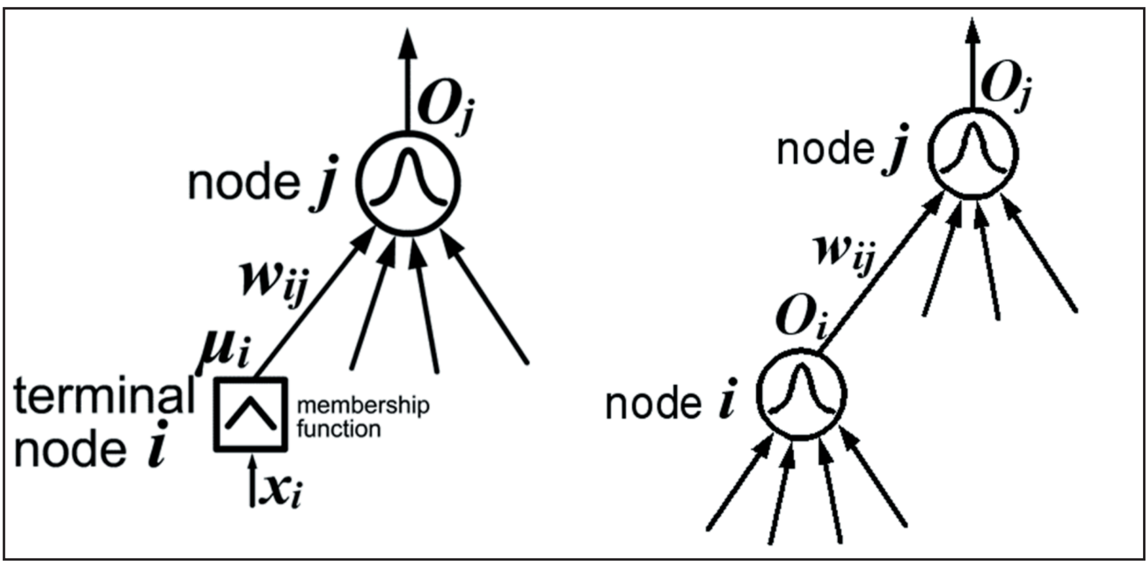


Figure 2. The detailed structure of a neural tree with respect to different types of node connections.

of a basis function to a node in the form of an external input. This is shown in Figure 2. The external weights coming to a node add up to 1. In other words, the sum of the weights is normalized to unity.

The centers of the basis functions are the same as the input weights of that node. Therefore, for a *terminal node connected to a nonterminal node*, we can express the nonterminal node output, denoted by O_j, as

$$O_j = \exp(-\frac{1}{2}\sum_i^n \left[\frac{X_i - w_{ij}}{\sigma_j}\right]^2) \qquad (3)$$

which, because of (2), becomes

$$O_j = \exp(-\frac{1}{2}\sum_i^n \left[\frac{w_{ij}(\mu_i - 1)}{\sigma_j}\right]^2) \qquad (4)$$

where j is the nonterminal node number; i denotes the i-th input to the node; μ_i is the output of the terminal node; wij is the weight associated with the i-th terminal node and the nonterminal node j. A detailed structure of a neural tree with respect to different types of node connections is shown in Figure 2.

For a *nonterminal node connected to a nonterminal node*, (3) becomes

$$O_j = \exp(-\frac{1}{2}\sum_i^n \left[\frac{w_{ij}O_i - w_{ij}}{\sigma_j}\right]^2) \qquad (5)$$

and further

$$O_j = \exp(-\frac{1}{2}\sum_i^n \left[\frac{w_{ij}(O_i - 1)}{\sigma_j}\right]^2) \qquad (6)$$

We can express (4) and (6) in the following forms, respectively.

$$O_j = \exp(-\frac{1}{2}\sum_i^n \left[\frac{(\mu_i - 1)}{\sigma_{wj}}\right]^2) \qquad (7)$$

and

$$O_j = \exp(-\frac{1}{2}\sum_i^n \left[\frac{(O_i - 1)}{\sigma_{wj}}\right]^2) \qquad (8)$$

where

$$\sigma_{wj} = \frac{\sigma_j}{W_{ij}} \qquad (9)$$

A further description of the formation of a neural tree as described above can be found in Ciftcioglu and Bittermann (2009).

A neural tree can represent a broad class of feed-forward networks with or without layered structure. The tree structure involved in this work is a layered one; it allows for easy exchange of substructures by standard subtree variation operators without affecting the building blocks. Input from any sublevel to any upper level is possible (Figure 3).

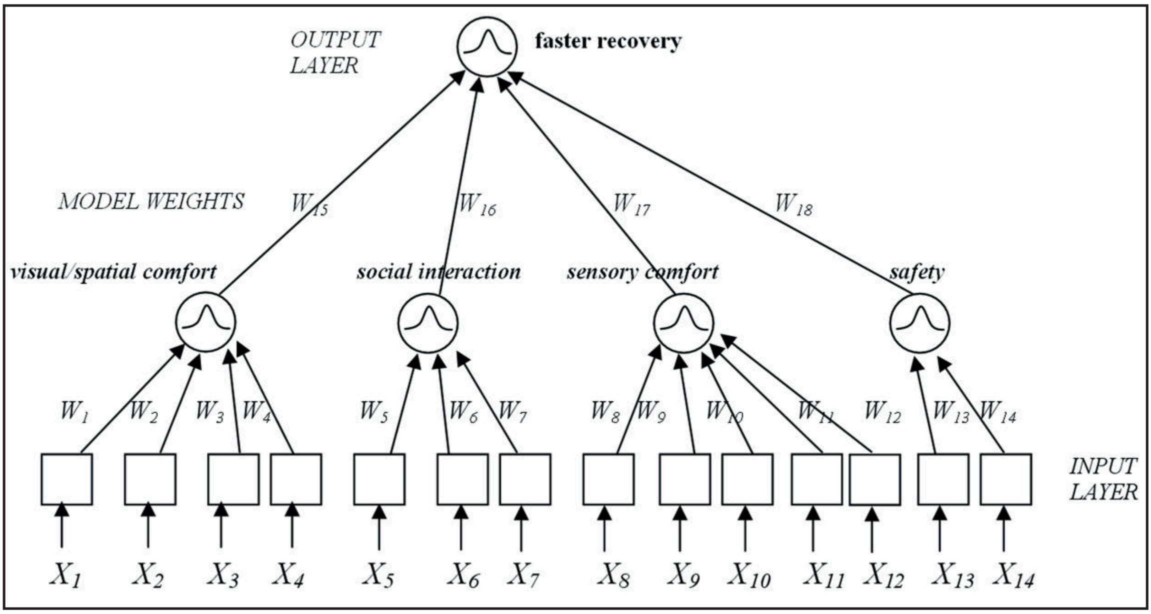


Figure 3. A configuration of the fuzzy neural tree as a feed-forward knowledge model.

Connection between nodes at the same level is also allowed. However, feedback from any upper level to a sublevel is not allowed. By means of this basic configuration, the levels are clearly defined in a structure of any complexity (Ciftcioglu & Sariyildiz, 2006).

Given a particular composition at the input level, with appropriate weights one output would result, which in this case would be the prediction of recovery time based on provided (input) context. In other words, the output would be a performance indicator of that particular hospital context.

It is important to note that this type of knowledge modeling is also flexible and open, because it is expected that new insights will appear and it should be possible to easily incorporate this new evidence in a knowledge model or improve the reliability of outcomes as new evidence becomes available.

Figure 4 presents a fictive knowledge model that represents the current evidence on a specific subject. Figure 5 demonstrates the flexible and open structure of the knowledge model, which enables the expansion of the model as new evidence appears. The open form of the knowledge model provides flexibility, meaning that as new, relevant evidence appears it can be included in the knowledge structure with minor adjustments of the local weights.

This approach has many advantages:

- It enables efficient knowledge management.
- It reuses the same knowledge for measuring the performance of different contexts/hospitals.

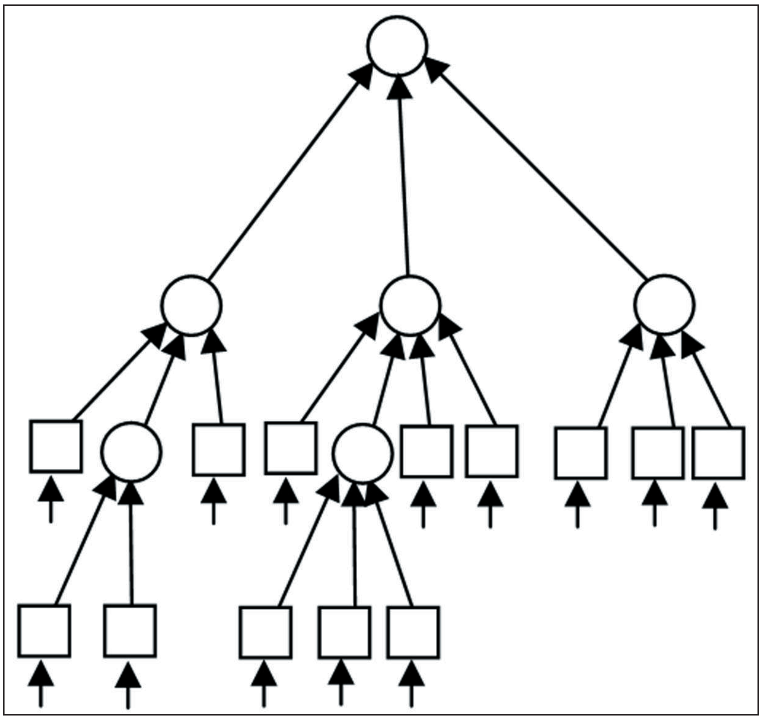


Figure 4. Basic knowledge model.

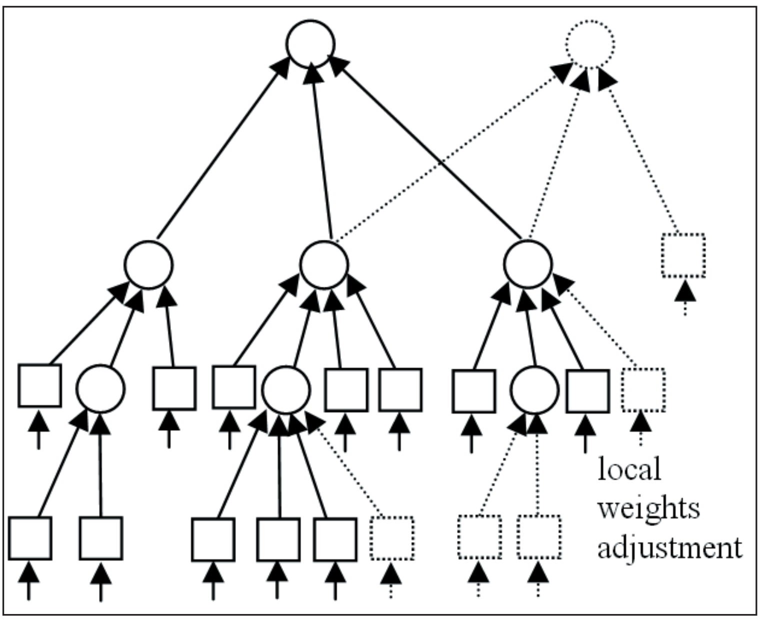


Figure 5. Expanded knowledge model.

- The effect of a certain design change is directly calculated and evident to the end user, showing immediately the performance of the total "design composition."
- The sensitivity analysis provides a feedback to the user regarding which input needs to be altered to improve the outcome.
- The fuzzy neural tree structure is flexible and can deal efficiently with the previously mentioned information explosion, because new insights appear very quickly and can keep end users up to date with new insights.

This type of knowledge modeling has already been applied to the healthcare domain (Durmisevic & Ciftcioglu, 2007; Durmisevic & Durmisevic, 2007). In this particular example, a FlexTool was developed that enables the measurement of a building's transformation potential. The Netherlands Board for Healthcare Institutions (CBZ, 2008) currently uses this tool to evaluate the transformation potential of existing nursing homes. It can also be used during the design of new buildings to optimize various design aspects and maximize flexibility.

The proposed methodology is a computational approach that makes it possible to predict the performance of a certain environment, considering the presence of numerous aspects at the same time, and therefore taking into account the cumulative effect of various design features on final outcomes. The performance of a knowledge model can be tested in different hospital contexts, so the final model can be evaluated and calibrated. The steps necessary for such knowledge modeling are described in the following section, including a hypothetical case study to explain the added value of the model and ways to interpret model outcomes.

Required Steps for Knowledge Modeling

There are three major steps for this type of knowledge modeling:

1. Developing a database based on found evidence (fuzzification of the evidence);
2. Determining model weights using expert assessment and the AHP;
3. Testing/evaluating the model and, if necessary, calibrating it.

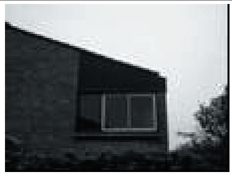
Additional explanation of these steps is provided to aid comprehension of the basic principle behind this type of expert-driven knowledge modeling.

Developing a Database Based on Found Evidence

To develop a database, it is first necessary to classify the aspects to be placed in a model and to determine the level of detail for each one. Level of detail is generally determined by the best available evidence for a particular aspect. Assume that one wants to operationalize the findings of Ulrich (1984), in which views of nature are preferred to the view of a brick wall. In this study it is shown that, in comparison with the group of patients who had a view of a wall, the patients with the tree view had "shorter postoperative hospital stays, had fewer negative evaluative comments from nurses, took fewer moderate and strong analgesic doses, and had slightly lower scores for minor postsurgical complications" (p. 421). In the model discussed in this article, this would be the input value X_4 (see Figures 1 and 3). The authors grade the views from the window on a scale from 0 to 1. The nature view is 0.9, and the brick wall is 0.1. Zero and 1 are not assigned, because it is assumed that there might be better or worse types of views than the one in the study; however, they are assigned values that are close to the extreme. One can assume that in between is a combination of the two, where, for example, in one view nature dominates the built environment and in another the built environment dominates nature. Table 2 provides a simplified example of grading the views from a window. It is only a start and a rough approximation of the reality. As new insights appear, grading can be calibrated and refined.

One can imagine that there are other aspects related to a view from a window such as privacy, openness, refuge, or prospect. A good score on one aspect of a view does not necessarily mean good scores on other aspects. Some aspects of a view may be more important than others; this

Table 2. Examples of Views and Associated Grading

View from a window				
grading	0.9	0.7	0.45	0.1

would be reflected in calculated weights and result in a change to the model. Instead of input X_4, there would be a connecting node "view from a window" and new threads such as privacy, openness, prospect, and refuge.

To ensure more comprehensive and accurate grading, one should define several fuzzy functions that represent the relationships between:

- View from a window and distance from objects (This may have an impact on the aspects of privacy and its subcomponent, openness.)
- Distance to an object and type of object (sky, trees, built environment, people) in relation to privacy, refuge, and positive distraction
- Percentage of buildings versus vegetation.

Figure 6 is an example of a function applied to openness, where distance to another building is considered. The *x* axis indicates a distance in meters, and the *y* axis contains the values between 0 and 1, where 1 is the best grade and 0 is the least desirable solution for this particular example.

Again, one could make a further refinement by specifying density distribution in relationship to openness and distinguishing different objects such as buildings, trees, people, or other objects. For different objects, different fuzzy functions that best represent the relationship to openness can be used. Together these form the database of a knowledge model.

This example demonstrates a way to move from a rough approximation of the reality to a more precise one. This enables the model to become more accurate over time. First grading is a rough approximation (Table 2); but by refining the different relationships between aspects a more refined approximation can be obtained, leading eventually to more accurate results (Figure 7).

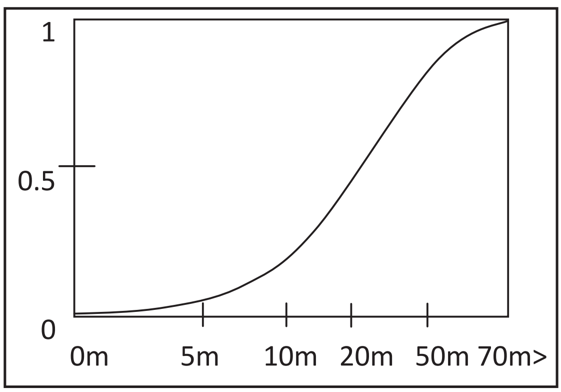


Figure 6. Sigmoid function describing distance of an object in relation to openness.

Table 3. Model Weights W_{15}–W_{18}

Aspects	Social interaction	Spatial comfort	Sensory comfort	Safety
Weights	W_{15} 0.2325	W_{16} 0.2425	W_{17} 0.255	W_{18} 0.270

Determining Model Weights

The establishment of a database does not provide knowledge in a form that is useful for practitioners. The database contains a lot of information, but no rules regarding how to combine the numerous aspects. To establish rules, model weights must be determined, thereby enabling the move from fragmented knowledge bits to active and integrated knowledge application.

AHP is a method introduced by Saaty and colleagues (1981, 1982) to calculate the priority vector that allows the relative importance of aspects to be established. This is done by a paired comparison of all aspects, and AHP makes it possible for experts to compare two aspects at a time and indicate their relative importance. In other words, experts elaborate on two aspects at a time to determine which is more important. This process continues until all aspects have been evaluated in a paired comparison. The grading after each cycle is recorded in a matrix, which is thereafter processed using AHP. This is an excellent exercise to bring together various experts across the AEC industry and from the medical and social sciences to discuss the relevance of the aspects and to support their arguments with credible evidence. This is one of the main advantages of this approach, because it brings various disciplines together to try to determine the issues most relevant to the healthcare domain.

To determine model weights, the authors follow Maslow's reasoning, considering all levels in the pyramid important, but giving a slight preference to one over the other. Table 3 provides an example of the weights W_{15} to W_{18}, where safety has the highest weight. Indeed, according to the AHP method, the sum of the weights should be 1.

Other weights (W_1 through W_{14}) can be established by field experts, again using the AHP method. The processing of information takes place in the connecting nodes, as explained in the previous section.

Model Testing and Calibration

Testing should be done via case studies; data should be collected on site and used as input to the model. The final step is to compare patient outcomes in different environments and calibrate the model, if necessary.

Arranging all of these pieces of information into a model creates an efficient, generic knowledge model that can be used for different building projects. It is both specific and generic at the same time. It is specific in the sense that knowledge is developed for a particular purpose—in this case, taking into account faster patient recovery. At the same time it is generic, because once a knowledge model is established, it can be reused for any design that considers

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Table 4. Hypothetical Case Study of a Patient Room

Dimension	Aspect	Characteristics	Grading Case 1 Baseline	Effect of Change for Case1 Improving Lounge	Effect of Change for Case1 Improving Art
Visual/spatial comfort	X_1 Nature	Mixed view (nature/buildings in distance)	0.75	0.75	0.75
	X_2 Art	not present	0.1	0.1	0.95
	X_3 Spatial organization	Privacy	0.95	0.95	0.95
	X_4 Windows	Informative view	0.95	0.95	0.95
Social interaction	X_5 Family involvement /interaction with family	Single room	0.95	0.95	0.95
	X_6 Interaction with staff	Single room	0.95	0.95	0.95
	X_7 Lounge	not available	0.1	0.95	0.1
Sensory comfort	X_8 Noise day	38 dB	0.90	0.90	0.90
	X_9 Noise night	30 dB	0.95	0.95	0.95
	X_{10} Temperature	22 C	0.95	0.95	0.95
	X_{11} Light	1500 lux	0.95	0.95	0.95
	X_{12} Air quality	10 L/s	0.90	0.90	0.90
Safety	X_{13} Material	Isolation	0.80	0.80	0.80
	X_{14} Spatial organization	Single room	0.95	0.95	0.95

the faster recovery of patients as a performance indicator.

Case Study and Model Interpretation

A hypothetical case study of a patient room is presented in this section to illustrate the potential application of the model and to demonstrate the added value.

Let us assume we have a patient room with the attributes provided in Table 4, using the values of baseline Case 1 as the model input. The first thing to do is to assess the current performance of the design with existing data on patient recovery. This could be an actual case where a designer wants to improve the performance of an existing building, or it could be during the design stage where a designer would like to test his/her design hypothesis. Feeding the input data into the model provides two important outcomes: The first is the estimated performances of the five dimensions of interest, such as patient recovery as a final dimension and its subdimensions safety, sensory comfort, social interaction, and visual/spatial comfort. (See Figure 7.) The performance of this baseline (Case 1) design on a scale between 0 and 1 in terms of patient recovery is estimated to be:

Pr (baseline Case 1) = 0.8237

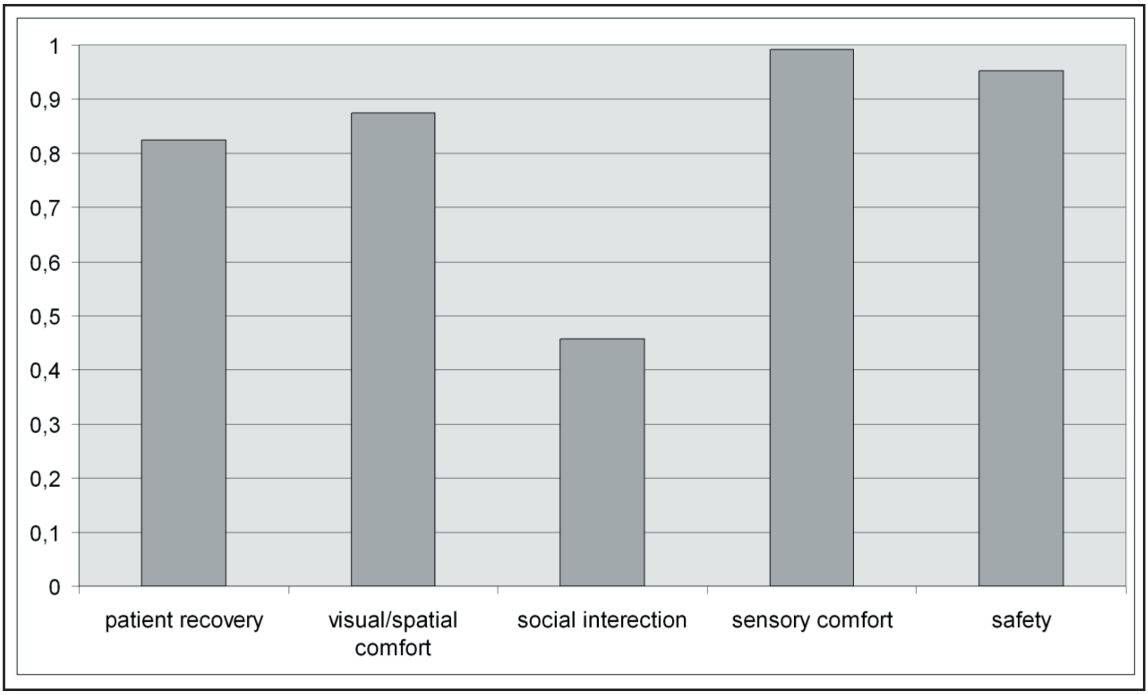

Figure 7. Calculated values for output nodes.

The second result is that of sensitivity analysis, a method used to determine the dependency of the output of a model on the information fed into the model (Saltelli, Chan, & Scott, 2000). The result is a hierarchical order of aspects, where the effects of each particular aspect on the outcome in a given context are calculated (Figure 8).

Following is the hierarchical order of aspects resulting from sensitivity analysis (in descending order), as seen in Figure 8:

7 13 14 2 5 6 1 12 8 3 4 9 10 11

This performance may be deemed satisfactory and in conformity with the current budget, or additional improvements may be desired. What does the hierarchical order indicate? It indicates that the greatest impact would be achieved by investing in aspect number 7, which in this particular case is the lounge, meaning that a space that promotes socialization and encourages a patient to leave his room should be provided. The sensitivity analysis tells us that this improvement would have the highest impact on patient recovery, taking into account all other aspects (other things being equal). But what would the performance of the modified Case 1 be (with the added lounge)? The results of this outcomes and sensitivity analysis are shown in Figures 9 and 10.

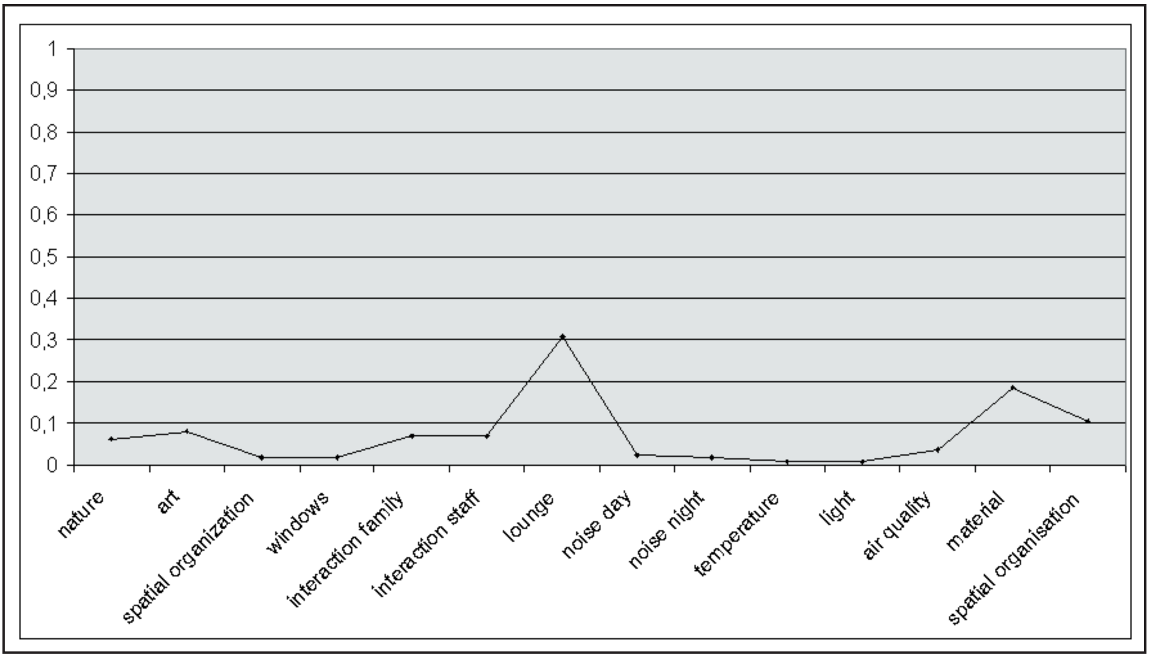

Figure 8. Sensitivity analysis of aspects

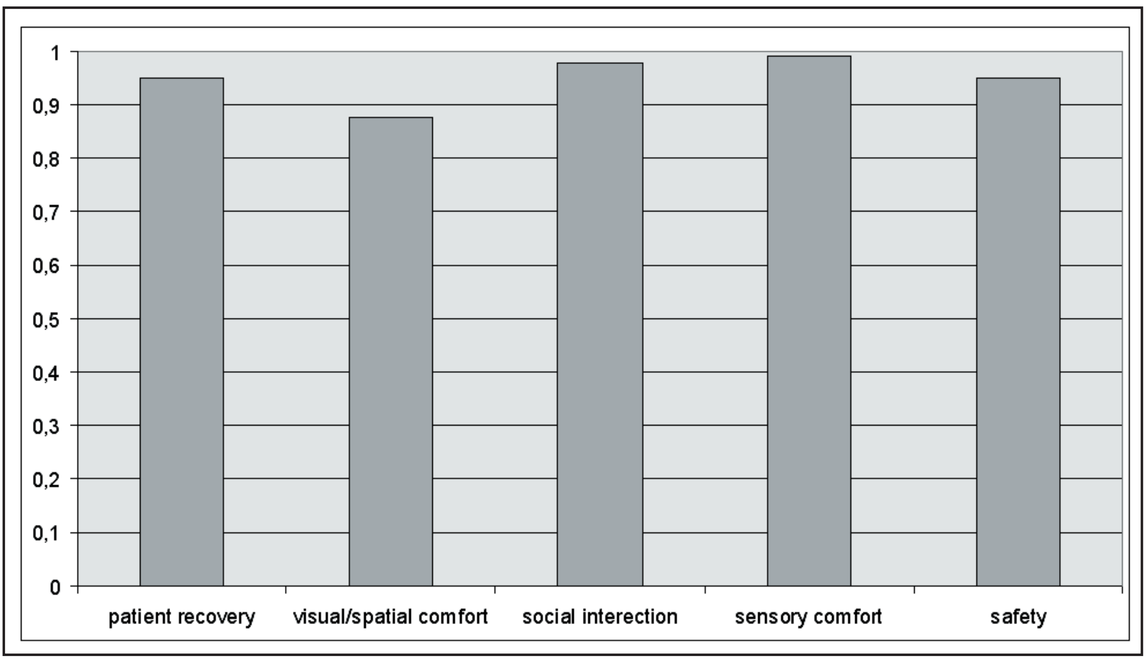

Figure 9. Calculated values for output nodes.

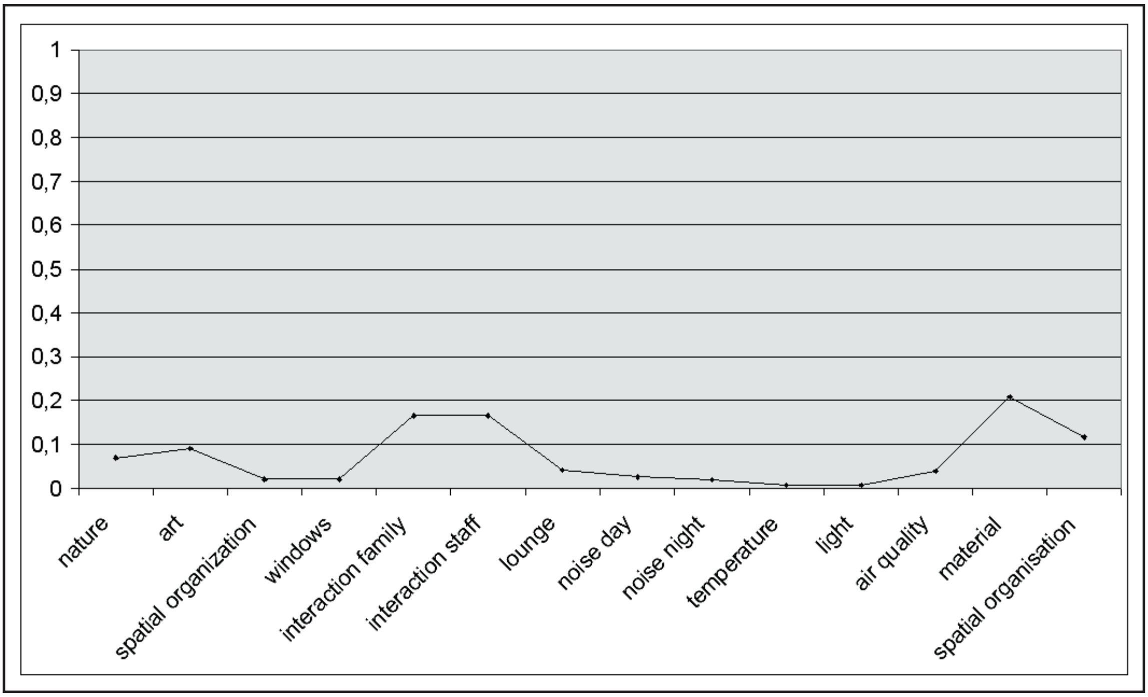

Figure 10. Sensitivity analysis of aspects.

If the addition of a lounge at the department improved input from 0.1 to 0.95, the estimated performance of the design would be:

Pr (Case 1/lounge) = 0.9503

This is an improvement of about 15% compared to the previous case. The new sensitivity analysis reveals a different hierarchy, and the related effects of each individual aspect:

13 5 6 14 2 1 7 12 8 3 4 9 10 11

To illustrate, the input data provided for Case 1 should be reanalyzed. Inspection of the input data reveals that two aspects of the design have low scores: the aspects of lounge and art. For both aspects, the input value on a scale from 0 to 1 is 0.1.

Consider the following scenario: A designer is not in possession of such a model, yet somehow he/she knows that the design scores badly on these two points. The budget for improvements is limited, making it possible to invest only in art or a lounge. The designer is in a dilemma. Which change would be most effective? Which investment would be wiser at this moment, taking into account all other aspects? The designer chooses the first option and invests in placing art objects such as paintings in the department.

The effect of the lounge is already known. The outcomes for the modified Case 1, where the aspect of art is improved, are shown in Figures 11 and 12.

If art is placed in the department, input data would change from 0.1 to 0.95, and the estimated performance of the design would be:
Pr (Case1/art) = 0.84682

The same investment can significantly affect overall performance differently. In this respect, performance-based tools can provide support essential to the AEC industry. This is an improvement of about 2.5% compared with the original baseline situation. This example illustrates the impact of two aspects on a final outcome and shows that the same investment can significantly affect overall performance differently. In this respect, performance-based tools can provide support essential to the AEC industry.

Conclusions

The next step for research on healing environments and EBD should be to study environmental aspects in a holistic way, using knowledge technology that deals adequately with both existing and new information. It goes without saying that the success of the knowledge model tool is highly dependent on the credibility of the data provided at the input of the model. The inputs should be from rigorous studies, and users of this tool should be knowledgeable enough to critically and credibly interpret the research they are using as source data. Some designers may argue that the use of EBD makes it possible to standardize best practices to the point where designers are not pushed to innovate. This might suggest that, using a knowledge modeling tool such as the one proposed in this paper, designers will recreate the same environments repeatedly, because the recommendations and weights assigned by the knowledge modeling tool suggest specific design recommendations each time. Instead, this tool provides an added value for the field rather than a limitation, because there will be an appropriate neural tree for any design. It can be used for two purposes:

1. To support decision makers/designers by indicating the direction one should take to improve the current situation/poorly performing buildings in terms of patient recovery;
2. To use when designing/planning a new facility to assess the outcome based on inputs provided for a particular design and taking into account the specifics of a particular site.

In the first case, the starting point is an existing building that, because of poor performance in terms of patient recovery, should be improved. This tool can provide quick insight into the best possible direction simply by analyzing the existing situation and proposing the most effective change. In other words, it can provide in hierarchical order the effect of various factors on patient recovery. Based on the results of sensitivity analysis, one may search for an optimal series of measures to achieve the best possible result for a particular context or decide to invest only in one particular design aspect if the gains are sufficient and output scores are improved.

In the case of a new facility, the tool provides guidance for designers to double-check whether their

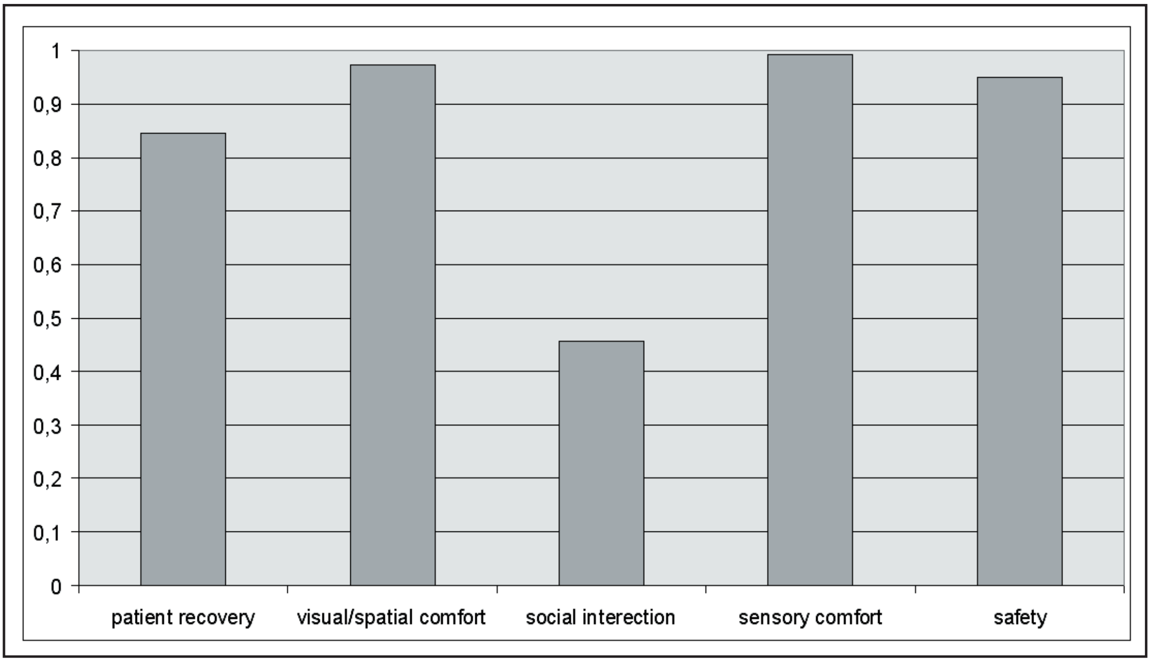

Figure 11. Calculated values for output nodes.

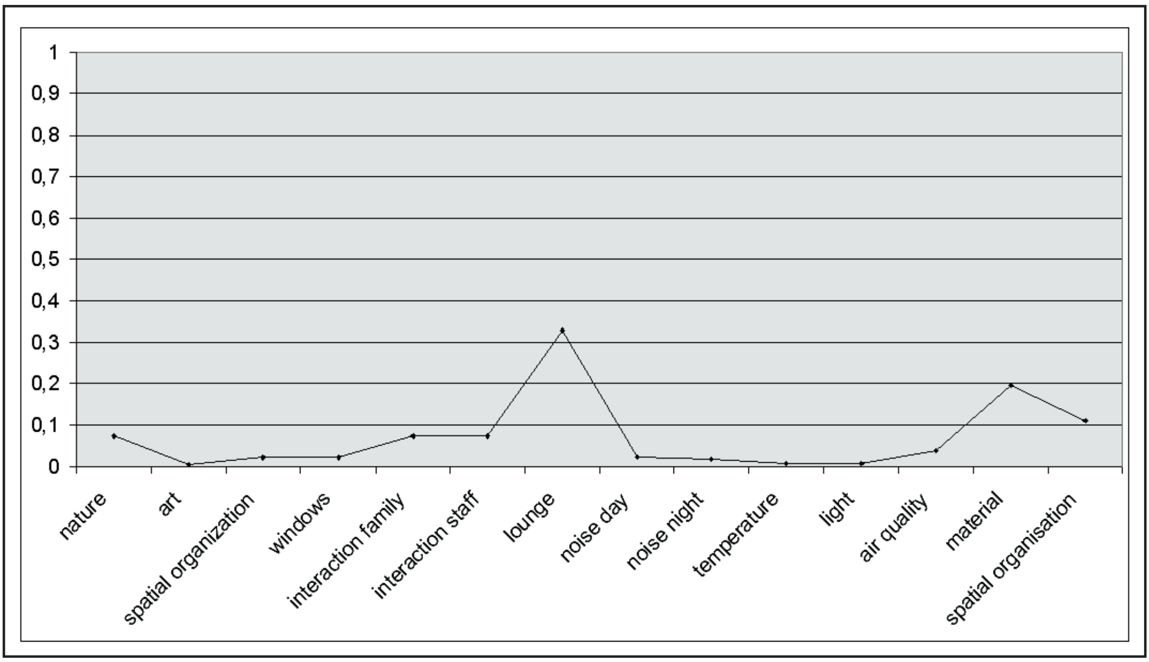

Figure 12. Sensitivity analysis of aspects.

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This tool increases design productivity and lends weight to design decisions during the design process, hypothesis testing, or post-occupancy.

design decisions are in line with state-of-the-art evidence in the field and, if necessary, improve certain aspects of the design to enhance its final performance. A designer can investigate different scenarios/design compositions and their performance. In conclusion, this tool increases design productivity and lends weight to design decisions during the design process, hypothesis testing, or post-occupancy.

In this work the authors used Maslow's hierarchy of needs as a starting point because of its relevance for the domain of EBD in healthcare. In Table 3 they assigned weights according to the theory, meaning that the dimension of safety, which is at the base of the pyramid (see Figure 1), has more weight than the dimension above it or at the top. In other words, each subsequent level of the pyramid has less weight than the preceding one. The type of knowledge modeling presented in this work should confirm Maslow's theory, and it does. Even the simple example of lounge and art improvement, which are from different levels of the pyramid, demonstrates the prevalence of the social dimension above visual/spatial comfort that is reflected in the outcome. Similar results can be expected if the issues related to safety are unsatisfactory and patient safety is therefore compromised. This unsatisfactory performance would be indicated in the output by downgrading the end performance more than when aspects from the upper level of the hierarchy are unsatisfactory.

By developing a holistic model, it is possible to finally understand why certain environments perform better than others. The main innovation of the knowledge modeling proposed in this paper is that it is based on the expected future performance of a total system rather than consideration of one aspect at a time. Only with such a holistic/systems approach and by applying knowledge technology is it possible to calculate the cumulative effect of individual aspects, simultaneously taking into account the presence of all other aspects and therefore presenting the actual context in a more realistic way.

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